

# A Study on Co-cured T-joint with Flange/Skin Debond

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The failure mechanism of a co-cured T-joint containing an initial debond between its skin and flange is investigated in this study. A finite element model of the T-joint was developed and analyzed to investigate its failure. Virtual Crack Closure Technique (VCCT) based on fracture mechanics approach was used to investigate the onset of debond growth. A failure criteria based on interlaminar peel strength was used to predict the failure inside the Bermuda Triangle. T-joint specimens with initial debond located between flange-skin interface were fabricated through a resin infusion process. Specimens were tested by applying pull loads on the web. Numerical results showed good correlation with test data.

## Nomenclature

$G_I$	=	Strain energy release rate (SERR) in Mode-I, J/m <sup>2</sup>
$G_{II}$	=	SERR in Mode-II, J/m <sup>2</sup>
$G_{IC}$	=	Mode-I Fracture toughness, J/m <sup>2</sup>
$G_{IIC}$	=	Mode-II Fracture toughness, J/m <sup>2</sup>
$S_{11}, S_{22}, S_{12} \text{ \& } S_{33}$	=	Stresses inside the Bermuda triangle, MPa

## I. Introduction

One of the most radical advantages of composite structures is low maintenance cost which comes by virtue of adhesive bonding of composite parts. A T-joint is formed by the intersection of two out-of-plane composite parts and serves as an out-of-plane load transferring unit (Fig. 1). T-joints in composite aircraft wing structures are formed in skin-rib, skin-stiffener and rib-spar connections. Damages or flaws in composite aircraft parts are inevitable. The presence of damages/cracks reduces the load carrying capacity of the structure [1]. Co-curing is a commonly used adhesive bonding technique which involves simultaneous cure of composite parts, for instance, co-curing of a stiffener and a skin in a composite aircraft wing [2]. In case of co-cured composite parts,

a damage/crack becomes significant when it is found at critical regions like flange-skin interface of T-joint. This is because, one of the major concerns with co-cured T-joints has been the high susceptibility of the skin-to-flange de-bonding and the failure process around the zone connecting the skin with the foot of the web, sometimes referred to as the 'Bermuda triangle' (Fig. 1). Such failures usually occur under the action of peel loads and hence necessitate studies on the behavior of T-joints. Tensile loads acting normal to web-flange interface are commonly referred to as T-pull loads. In a typical aircraft wing, such loads develop at skin-rib and skin-stiffener joints due to buckling of the skin panels or due to internal fuel pressure acting on the wing skin.

The objective of the current study was to investigate the failure mechanism of a co-cured composite T-joint containing an initial debond between its skin and flange. A finite element model of the debonded T-joint was created to study its behavior and numerical results were validated through T-pull tests.

## **II. Fabrication and Testing of T-joint**

A typical T-joint consists of a flange, web, the fillet zone and a skin (Fig. 1). The flange interfaces with the skin and the web provides an interface for attachment to the substructure and the fillet provides continuity of load transfer between the web and flange. The fillet radius plays an important role in determining the stress concentration at the junction of two co-cured composite parts [3]. Figure 2 shows the dimensions of the T-joint specimen considered in this study. Detailed view of the Bermuda triangle (BT), fillet region and debond location is presented in Fig. 3 along with layup sequence of skin and web. Six T-joint specimens were fabricated at CSIR-NAL through a patented resin infusion technique called VERITY [4]. During layup, a strip of porous release film (25 mm wide) was placed below the web on the capping layer to create debond of 25mm length. Three strain gauges were bonded to each specimen for measurement of strain during test. Strain gauge S1 was placed on the bottom face of the skin, strain gauges S2 and S3 were bonded to the two faces of the web (Fig. 4).

A pin loaded self aligning test fixture fabricated at Advanced Composite Division of CSIR-NAL was used for testing these specimens. T-pull tests were performed using a Universal Testing Machine under displacement control mode at a crosshead speed of 0.2 mm/min.

Figure 5 presents the behavior of T-joint specimens under pull loading. All six specimens showed consistent results. During the tests, it was observed that in all specimens failure initiated in the BT region by way of matrix cracks. This matrix cracking in BT region did not significantly affect the overall behavior of the specimen. However, it led to a small drop in load which is shown for two specimens in Fig. 6 (only two specimens' results are shown for sake of clarity). The onset of debond growth occurred at a higher load (Fig. 6). The loads

corresponding to BT matrix cracking and onset of debond growth are presented in Table 1. Final and complete failure of specimens occurred at even higher load (Figs. 5 and 6).

### III. Numerical Simulation and Validation

After the tests, the specimens were pulled further until complete separation of web from skin. It was observed that the debond which was expected to be symmetrical about web, had shifted by 4.5 mm towards one side because of an unintentional shift of the porous release film during cure. This offset in debond location was incorporated in the FE model. Mesh details of the 2-d plane strain model used for VCCT is shown in Table 2. The location of debond in FE mesh is shown in Figure 7. Material properties are given in Table 3. Local coordinate systems were defined for fillet, web, ply drop, BT and skin regions in order to correctly assign material properties to the corresponding region. A vertical displacement of 0.7 mm was incrementally applied at top of web with an increment size of 0.01 mm. All degrees of freedom were restrained at the ends of skin. CPU time taken to solve the model was less than 1 minute.

To investigate crack initiation in BT region, a failure criterion based on interlaminar peel strength was used [5]. According to this criterion, failure is expected when stresses inside BT in the matrix direction exceed interlaminar peel strength (ILPS). In this work, ILPS was assumed to be 25.5 MPa [5]. Stress contours inside the BT for a load of 2607 N are shown in Fig. 8. It is clear from Fig. 8 that the dominant component  $S_{11}$  reaches its critical value (ILPS) at this load.

VCCT approach was used to determine the critical load for debond growth [6]. VCCT computes energy release rates in all three fracture modes explicitly and separately. This technique is ideally suited for delaminations and debonds in laminated composite materials where failure depends on the mixed-mode ratio and propagation occurs in a laminate plane. Table 4 presents the SERRs calculated using VCCT for an applied load of 2792 N. Debond failure index calculated based on a simple power law (Eq. 1) is also presented in Table 4.

$$\text{Debond failure index} = \frac{G_I}{G_{IC}} + \frac{G_{II}}{G_{IIC}} \geq 1, \text{ for debond growth} \quad (1)$$

The loads corresponding to BT matrix crack initiation and onset of debond growth obtained from FE analyses are compared with test data in Table 5. Critical loads predicted through FE analysis show good correlation with test results.

#### IV. Conclusion

Damage tolerance is an important aspect for airworthiness certification and structural substantiation of composite aircraft structures. In case of co-cured composite parts, a damage/crack becomes significant when it is found at critical regions like flange-skin interface of a T-Joint. Co-cured T-Joints are susceptible to skin-to-flange debond and failure at the Bermuda triangle (BT) region which usually occur under the action of peel loads. The present study deals with understanding the behavior and failure of a co-cured composite T-joint containing debond. T-joint specimens were fabricated using resin infusion process. Debond was simulated by placing non-adhesive inserts between flange and skin plies. Specimens were tested under pull load. In all specimens, failure initiated at the BT region by way of matrix cracks. However, there was no discernable loss of stiffness or load carrying capability. This was followed by debond growth and later, final failure. Finite element analysis of the T-joint was performed to predict the failure of the T-joint. Failure of BT region was predicted based on interlaminar peel strength. Virtual crack closure technique was used to predict the onset of debond growth. Numerical results showed very good correlation with test data.

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Figures and Tables

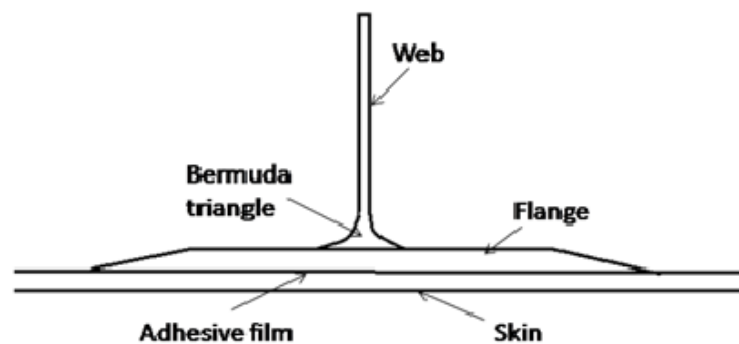


Fig. 1 Typical T-joint

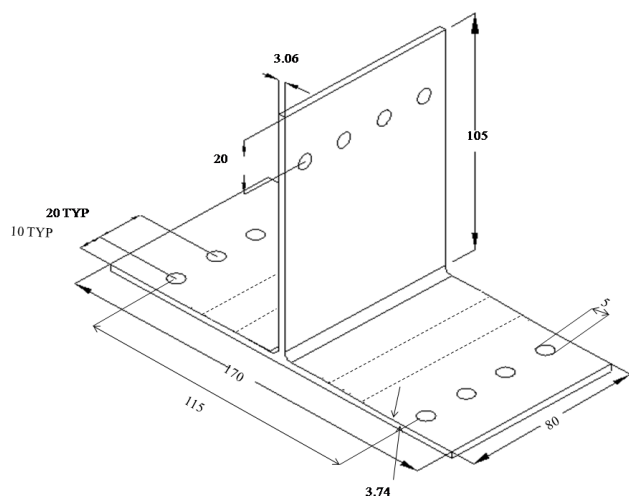


Fig. 2 Isometric view of the T-joint specimen (all dimensions in mm)

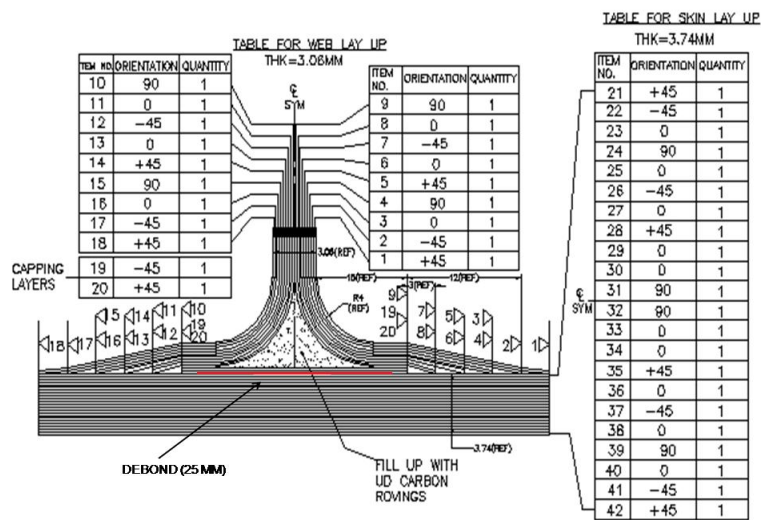
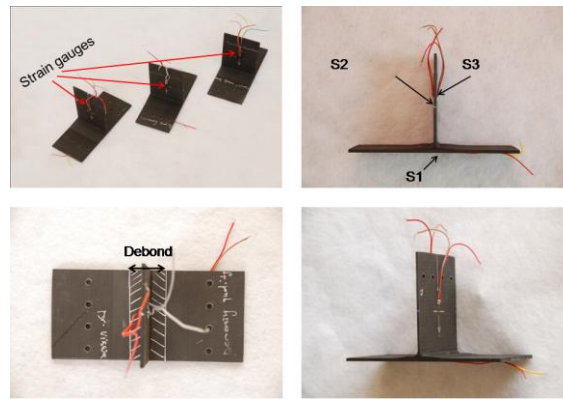
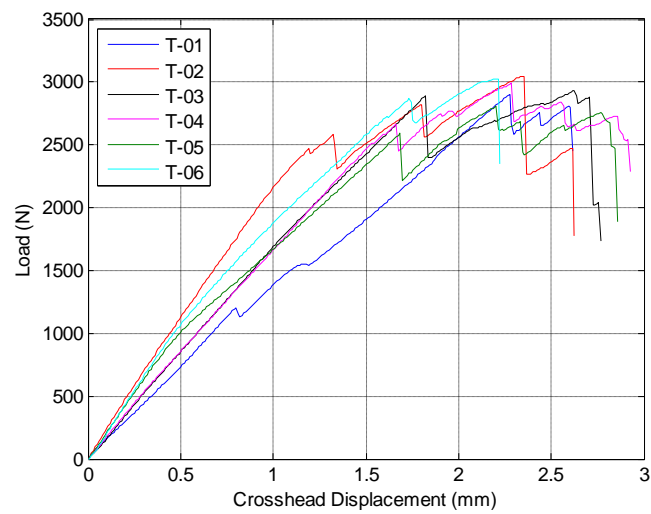


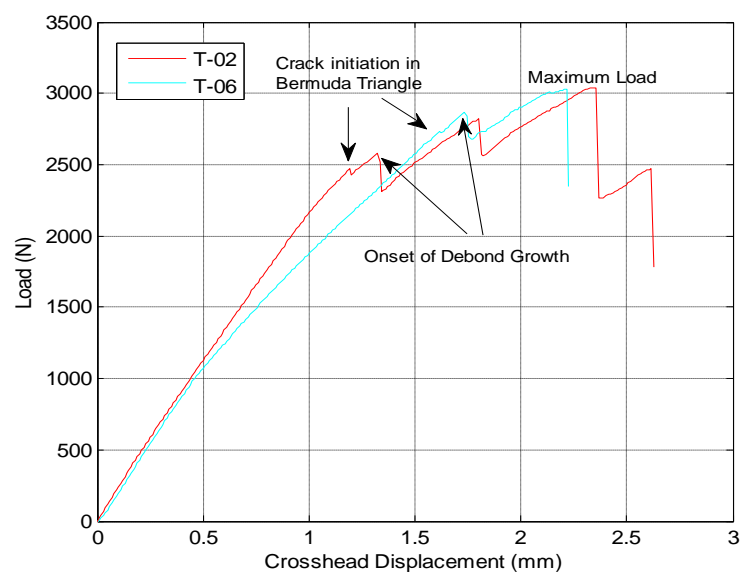
Fig. 3 Layup sequence of T-joint specimen



**Fig. 4 T-joint specimens: Fabricated & Strain gaged**



**Fig. 5 Load vs crosshead displacement**



**Fig. 6 Load vs Crosshead Displacement for specimens T-02 and T-06**

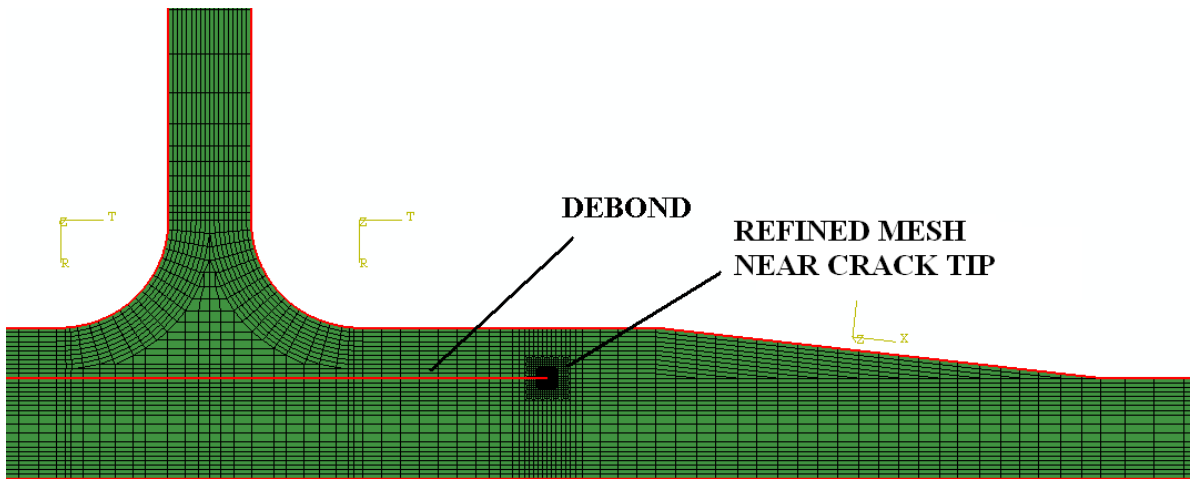


Fig. 7 FE Mesh with debond location

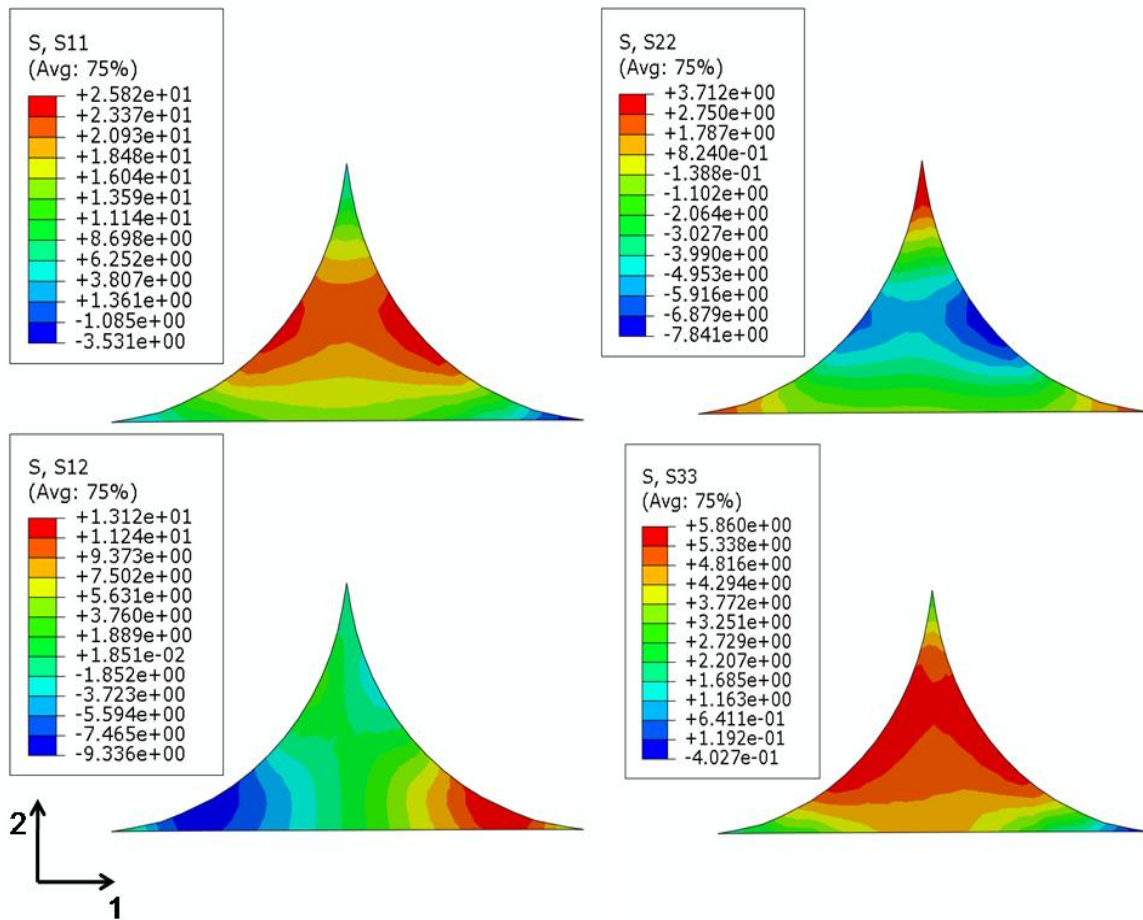


Fig. 8 State of stress inside Bermuda Triangle (Load = 2607 N)

**Table 1 Loads corresponding to BT crack initiation and onset of debond growth**

Specimen No.	Load corresponding to BT crack initiation (N)	Load corresponding to onset of debond growth (N)
T 01	2720	2903
T 02	2460	2580
T 03	2700	2890
T 04	2586	2665
T 05	2500	2590
T 06	2730	2870
Average load = 2616		Average load = 2750

**Table 2 Details of finite element mesh**

Total no. of elements	6430
Quad elements (CPE-4R)	6390
Tria Elements(CPE 3)	40
Total degrees of freedom	13414

**Table 3 Material properties used in FE analysis**

$E_{11} = 120 \text{ GPa}$	$E_{22} = 8 \text{ GPa}$	$E_{33} = 8 \text{ GPa}$
$\nu_{12} = 0.32$	$\nu_{13} = 0.32$	$\nu_{23} = 0.52$
$G_{12} = 3 \text{ GPa}$	$G_{13} = 3 \text{ GPa}$	$G_{23} = 3 \text{ GPa}$

**Table 4 SERRs calculated at debond tip using VCCT approach**

	Load = 2792 N			
	$G_I$	$G_{II}$	$G_{III}$	Failure index
Left debond tip	175.0	6.9	181.9	1.01
Right debond tip	36.2	65.0	101.2	0.24

**Table 5 Comparison of numerical results with test data**

LOAD (N)	FE	TEST (Mean)
Bermuda Triangle crack initiation	2607	2616
Onset of debond growth	2792	2750